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Bearing strength of autoclave and oven cured Kevlar/epoxy laminates under static and dynamic loading

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The pin bearing behaviour of woven Kevlar fibre-reinforced epoxy laminates, prepared by autoclave and oven curing methods, was examined under static and dynamic loading. Static bearing strength was determined as a function of bolt constraint and specimen geometry with particular attention to failure modes. The performance was very sensitive to lateral bolt tightening: a bolt with only a 'finger-tight' nut produced ~100% improvement in bearing strength, compared with the performance of a pin-loaded hole. Some specimens were hygrothermally conditioned and indicated a 10% deterioration in the bearing strength of the bolt-loaded hole. However, this was well below the magnitude of variation in strength which resulted under different methods of production. The fatigue endurance limit ($N \sim 10^6$) at 1 Hz was only achievable at stress levels equivalent to 25% of the maximum static bearing strength.

(Keywords: bearing strength; autoclave and oven cured Kevlar/epoxy laminates; static and dynamic loading)

INTRODUCTION

Successful adoption of bolted joints in composites depends on a clear understanding of pin bearing strength. There are various parameters to be considered, including material type and structure, specimen geometry and loading conditions. The effect of ply lay-up on bearing strength of the laminates has been examined for carbon fibre-reinforced plastics (CFRP)[1–6], glass fibre-reinforced plastics (GFRP)[4,7] and Kevlar fibre-reinforced plastics (KFRP)[8].

Work on the influence of geometric features, i.e. specimen width (w), thickness (t), end distance (e) and pin-hole diameter (d), has indicated that, for a given lay-up, the minimum e/d and w/d ratios must be provided, otherwise the potential bearing strength will not be realized. According to Collings[1], CFRP lay-ups of 0°/90°; all ±45°; 0°/±45°; and 0°/±60° configurations, under lateral constraint, would respectively require $(e/d) > 5$ and $(w/d) \geq 4$; $(e/d) > 4$ and $(w/d) \geq 8$; $(e/d) \geq 3$ and $(w/d) \geq 4$; $(e/d) \geq 3$ and $(w/d) \geq 5$. These values are corroborated for a 0°/90° lay-up[9] and for a 0°/±45 lay-up[10]. A different value, $(w/d) \geq 6$, for a ±45° lay-up and a degree of dependence of the (w/d) values on relative proportions of plies in 0°/±45° have been shown elsewhere[11]. In the absence of lateral constraint, the bearing strength is inversely related to the d/t ratio for most material systems[10]. The full bearing strength is realized at $d/t = 1$; however the possibility of the pin shear failure increases at $d/t < 1$.

The bearing strength, under laterally constrained bolts, increases gradually and reaches a 'plateau' value by avoidance of premature failure due to localized delamination or fibre disintegration into fibrils ('brooming'). In a 3 mm thick CFRP laminate, depending on the hole size, improvements of 60–170% have been measured[12] at a constraint pressure of ~22 MPa. Smith and Pascoe[4] have shown that for 1 mm thick CFRP laminates, covering a range of stacking sequences, the maximum bearing strength is only achieved by using clamping pressures greater than 35 MPa. These findings were corroborated in a recent study[6] on various woven and unidirectional carbon fibre/epoxy resin systems.

Various failure modes have been identified[1,13–15]: end-section bearing (crushing failure ahead of the bolt), net-section tension (tensile failure across the reduced section), edge-section shear (double shear out parallel to the direction of load), end-section cleavage (tear out or split forward of the bolt) and a tension–cleavage combination. A mixture of these modes may, of course, occur[9].

In this work, the pin bearing behaviour of woven

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Kevlar fibre-reinforced epoxy resin is examined under static and fatigue loading conditions. The static bearing strength is assessed as a function of specimen geometry and the lateral constraint applied to the bolt.

EXPERIMENTAL

Materials and specimens

Laminates of flat panels were prepared from (a) Kevlar 49-285 fibre/Fiberite MXM 7714 epoxy resin and (b) Kevlar 49-285 fibre/Brochier 1454 epoxy resin prepreg. The prepregs were in four-harness (or crowfoot satin) fabric form with ~52% by volume resin content.

Laminates were produced by autoclave curing and oven curing, for comparison. Each panel, ~3.0 mm × 240 mm × 400 mm, consisted of 10 plies in $(0°, 90°)_{10}$ lay-up. The stack was bagged, debulked under vacuum at the 5 and 10 ply stages, and then cured. Autoclave settings were 127 ± 5°C, 310 ± 35 kPa and 2 h. Oven curing was also conducted at 127°C for 2 h. A vacuum of 760 mm Hg (~100 kPa) was applied to the debulked stack of plies throughout the oven cure cycle. The heating and cooling of the production chamber were maintained at ~2.5°C min^{-1} in both cases. Laminates of ~2.8 and 3.3 mm were produced by autoclave and oven curing, respectively. The panels were inspected by ultrasonic C-scans in a water immersion tank. Void contents of ~1% in autoclave cured panels and >2% in oven cured panels were detected. Poor surface finish was in evidence in oven cured panels.

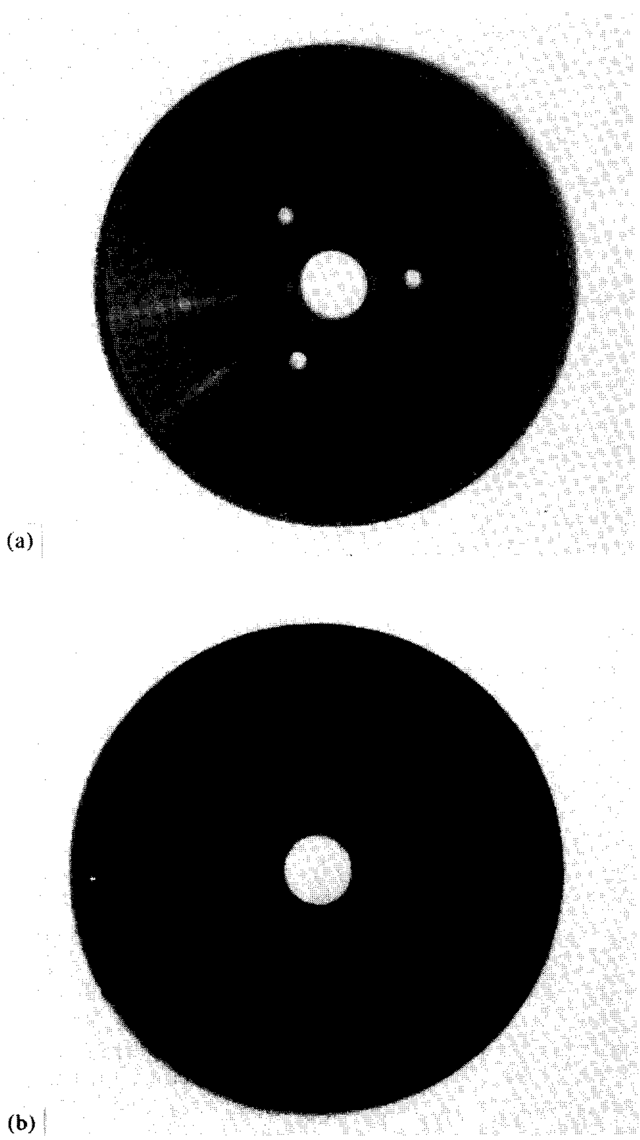

Figure 1 Diamond-tipped rotary wheels: (a) fresh tip; (b) worn tip

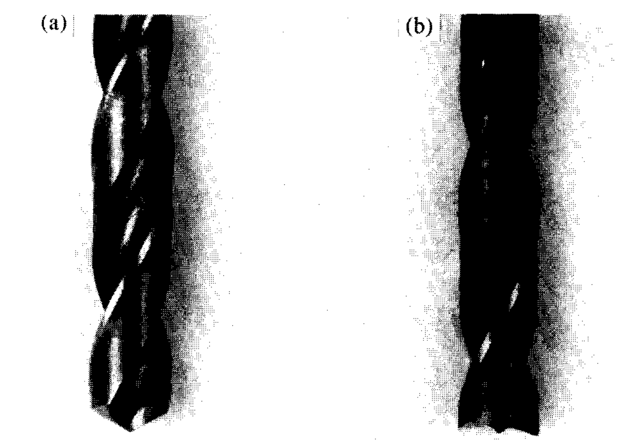

Figure 2 Drill bits: (a) standard; (b) modified

Standard coupons ~120 mm long and 30 mm wide were cut from the panels and centrally located holes of 4.8 mm diameter were drilled at 30 mm end distance. Specimens with different w and e dimensions were also prepared to yield $2 \leq w/d \geq 8.3$ and additional e/d ratios of 2 and 3.

Kevlar has excellent toughness and abrasion resistance, both of which create problems in the cutting of the prepreg and machining of the composite. The molecular arrangement within Kevlar fibres, in the form of weakly bonded radial sheets, results in fibrillation rather than clean cuts across the fibres. A diamond-tipped rotary wheel, for cutting test pieces, was found to suffer excessive tip wear (see *Figure 1*) and also caused localized burning of the material. An ordinary band-saw, running in reverse such that the heel of the saw teeth enter the composite first, produced smoother cut edges and was preferred for specimen preparation.

Special drilling procedures were also followed to avoid fuzzy edges. A high speed steel drill was modified as shown in *Figure 2* to provide three sharp contact points[16], and the specimens were drilled at 2400 rev min^{-1} on a backing of 25 Shere D hardness rubber. Cutting and drilling were both conducted in stages to avoid accumulation of swarf and to allow the tools to cool.

Test procedures

Static pin bearing strength. Tests were conducted with reference to ASTMD953 at room temperature of ~20°C, using an Instron machine in tensile mode. Hole displacement was measured using an extensometer. Load was applied at 1.3 mm min^{-1} via a 4.74 mm diameter pin. The pins were machined from high duty tool steel (Kayser Ellison 970) bars, hardened (by heating at 730°C for 0.5 h and at 970°C for 1 h and then quenching in oil at room temperature), and tempered by heating up to 250°C, rendering a Vickers hardness value of ~280.

Figure 3 shows a typical load–displacement curve and the relevant micrographs to illustrate the development of damage. Stress values, load/(dt), were determined corresponding to maximum load. The specimens were

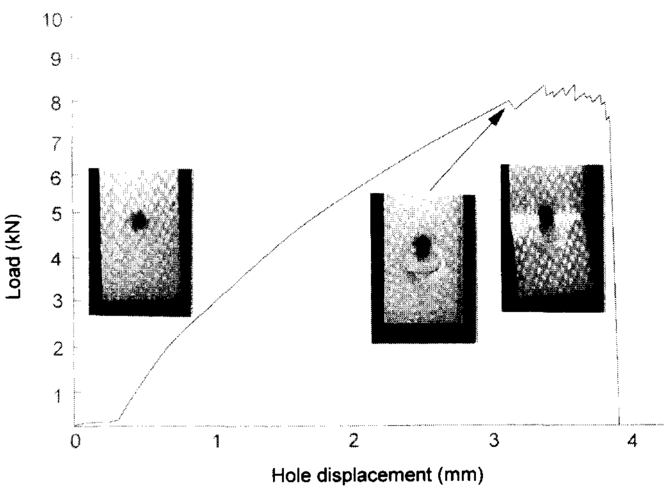

Figure 3 Typical load–displacement curve with associated photographs at various levels of load

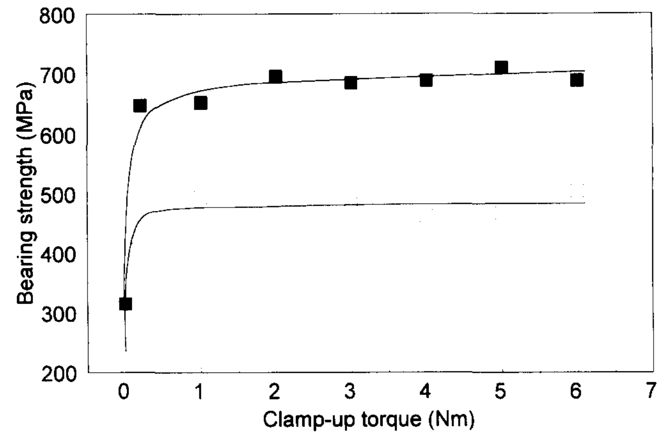

Figure 4 Bearing strength over a range of bolt clamp-up torque for Fiberite laminates: (■) autoclave cured; (□) oven cured

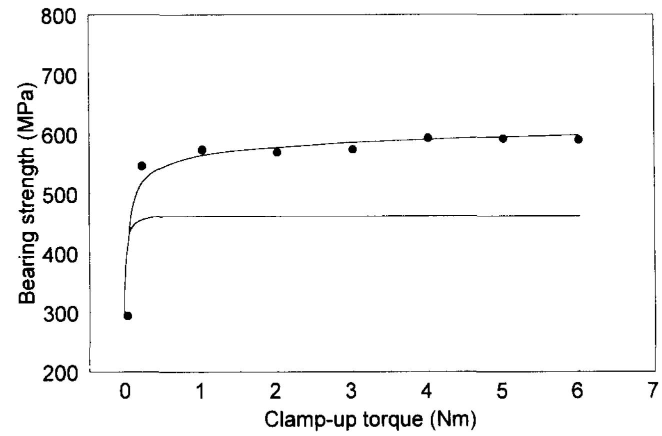

Figure 5 Bearing strength over a range of bolt clamp-up torque for Brochier laminates: (●) autoclave cured; (○) oven cured

prepared with finger-tight bolt lateral constraint (~0.2 N m torque). A set of specimens was further examined over a range of constraints corresponding to bolt torque values of 0–6 N m. The upper limit of the applied torque was dictated by pin thread stripping. The constraint pressure σ_{press} has been identified elsewhere[1], and based on the pin torque T and the constrained area, it becomes:

$$\sigma_{press} = T/[(\pi/4)\ Kd_p\ (d_b^2 - d^2)]$$

where $K = 0.2$ is a torque coefficient[17], and d_p, d_b and d are the diameters of the pin, clamping bush and the hole, respectively. Substituting average values of d_p = 4.74 mm, d_b = 15.5 mm and d = 4.8 mm gives:

$$\sigma_{press}\ (\text{MPa}) = 6.18\ [T\ (\text{N m})]$$

Additional specimens were hygrothermally conditioned in an environmental chamber set at 70°C and 95% relative humidity (r.h.) to a moisture absorption level of ~2%, and tested for comparison.

Dynamic pin bearing strength. Sinusoidal load–amplitude tests, on an Instron servohydraulic machine, were conducted at 1 Hz in positive-positive mode using a base load of 0.4 kN and a range of preset maximum loads. A lateral constraint of ~6 MPa (≡ 1 N m pin torque) was applied to the specimens. The tests were continued to full failure of the specimens or to a maximum cycle count of one million. Negligible temperature rise was recorded on the specimens at 1 Hz cycling.

RESULTS AND DISCUSSION

Static bearing behaviour

Influence of lateral constraint. The bearing strength of the autoclave and oven cured laminates was investigated over a range of lateral constraint (0–37 MPa). *Figures 4* and *5* show that the bearing strength increased considerably (by ~100%) by mere finger tightening of the bolt (~1.2 MPa lateral constraint). Any additional increase in strength with further bolt tightening was commensurate with the magnitude of the applied lateral constraint which is transferred to the laminate and improves the resistance of the laminate to compressive (and through-the-thickness tensile) deformation. However, the oven cured laminate specimens did not indicate any lateral constraint induced improvement beyond finger tightening. The oven cured laminates are underconsolidated compared with the autoclave cured laminates – as indicated by the greater void content, poor surface finish and greater laminate thickness (by ~0.5 mm). Therefore, the range of clamping pressures applied here can probably be accommodated by the lateral compliance of the underconsolidated laminates rather than altering effective clamping; and hence a levelling off in the bearing strength was indicated beyond a finger-tight clamping pressure.

A transition in the failure mode was noted and coincided with the change in the bearing strength pattern (see *Figure 6*). All the laminates exhibited a bearing-type failure with localized delamination, resulting in pronounced brooming on the loaded edge of the pin, due to low compressive strength of the Kevlar fibre. Bolted joints, even if only finger-tight, prevented laminate brooming and resulted in a significant increase in the failure load. Examination of the finger-tight bolted specimens at various stages of the bearing test (see *Figure 3*) showed limited initial bearing failure at the hole edge, which progressed to remote bearing failure at the washer edge with continued loading. The material gathered at

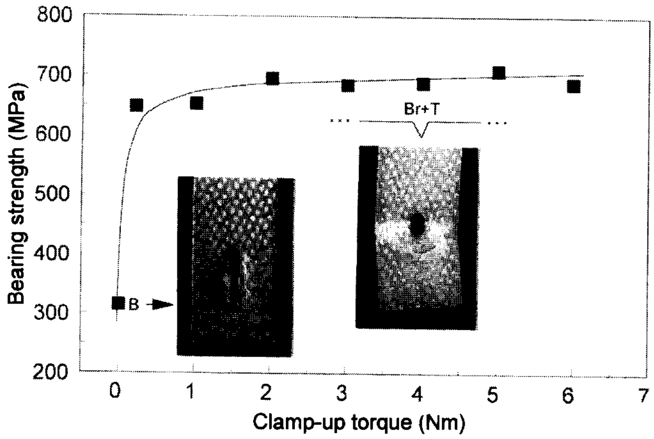

Figure 6 Illustration of transition in bearing behaviour with bolt clamp-up variation (failure-mode designations are defined in *Figure 10* caption)

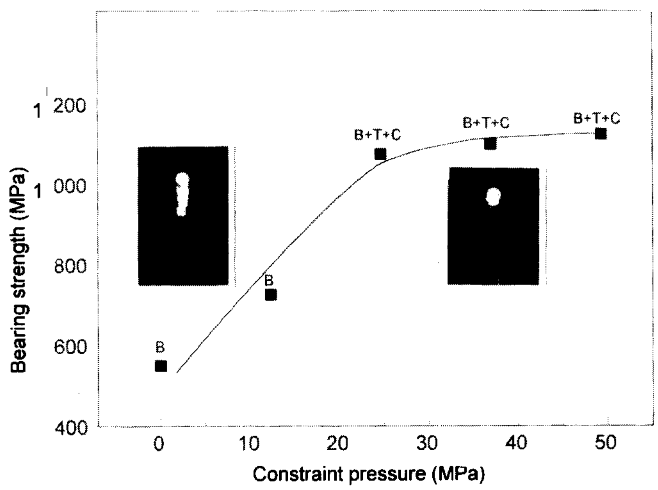

Figure 7 Bearing strength over a range of constraint pressures for CFRP[6]

the washer edge hinders further displacement of the bolted pin and the ultimate failure occurs in the net tension mode. At higher bolt clamping pressures the displacement of the joint was not accompanied by any obvious initial bearing at the hole edge but, as under the finger-tight condition, once sufficient material was dislodged and had accumulated at the edge of the washer, then net tensile failure occurred. Therefore, it is apparent that lateral clamp-up produces a transition in the ultimate failure mode from bearing in the pinned only joints to tensile in the bolted joints. In a previous study a similar transition was reported for CFRP (see *Figure 7*), although the level of the lateral constraint required to effect the transition was much higher in CFRP (≥25 MPa depending on the laminate thickness and the lay-up sequence) than in the Kevlar composites considered here (which only required finger-tightening for the transition).

Hygrothermally conditioned specimens (at 70°C/95% r.h. for 70 days, resulting in 2% moisture content) were tested under a lateral constraint torque of 2 N m. The mode of failure was similar to that of as-cured specimens and an ~10% reduction in bearing strength was indicated, (see *Table 1*). Obviously the moisture-induced weakness in compressive[18], interlaminar shear[13,18] and bearing[19] strengths, demonstrated using CFRP, becomes less critical in laterally constrained bolted joints.

Table 1 Results of hot/wet (H/W) conditioning

Laminate type	Specimen condition	Bearing strength (MPa)
Fiberite	As-cured (autoclave)	686
Fiberite	H/W (autoclave)	576
Fiberite	As-cured (oven)	480
Fiberite	H/W (oven)	450
Brochier	As-cured (autoclave)	569
Brochier	H/W (autoclave	535
Brochier	As-cured (oven)	481
Brochier	H/W (oven)	458

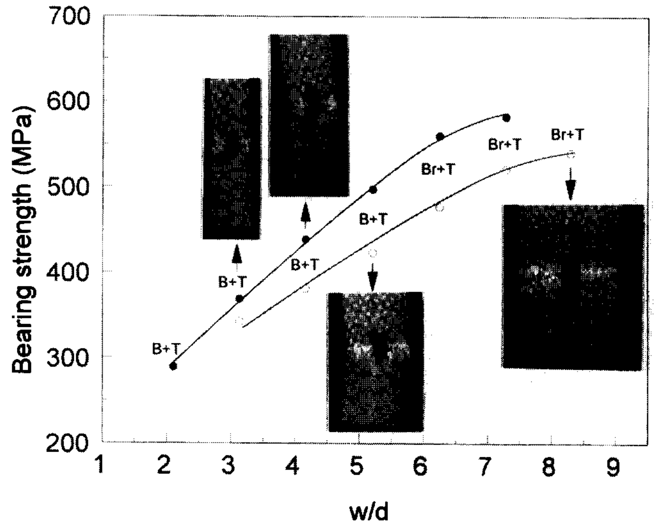

Figure 8 Variation of bearing strength with *w/d* for Brochier laminates: (●) autoclave cured; (○) oven cured

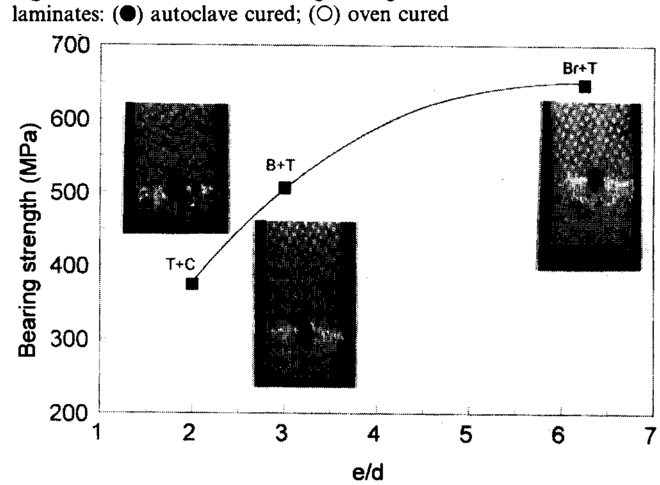

Figure 9 Variation of bearing strength with *e/d* for autoclave cured Fiberite laminates

Table 1 and *Figures 4* and *5* also clearly show that, in comparison, the oven cured laminates produce much inferior bearing performance (reductions in strength of ~15 and 30% were indicated, respectively, for the Brochier and Fiberite systems). Furthermore, in more fully consolidated (i.e. autoclave produced laminates), clear variations in bearing strength (by ~15%) are indicated between the two types of matrices considered here.

Influence of specimen parameters. The influence of the specimen parameters on bearing strength and modes of failure was examined with finger-tight bolted joints. *Figures 8* and *9* show that the bearing strength varied with the specimen width and end distance in the familiar fashion. To achieve optimum bearing strengths, *w/d* > 6 and *e/d* > 3 are required for the autoclave cured lami-

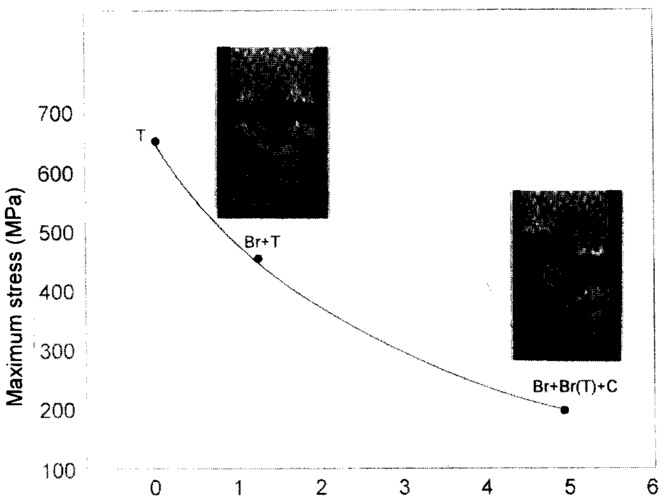

Figure 10 *S–N* curves for autoclave cured Fiberite laminates with associated photographs at various stress levels. Failure modes are designated in *Figures 6–13* as B (bearing), T (tension), C (cleavage), S (shear), Br (remote bearing) and Br (T) (tensile failure which coincides with the remote bearing rather than across the reduced section)

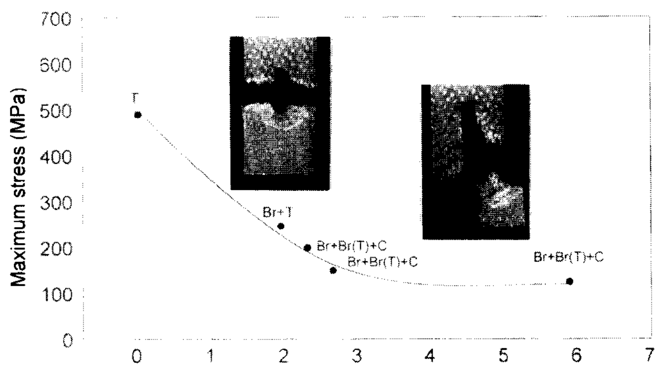

Figure 11 *S–N* curves for oven curved Fiberite laminates

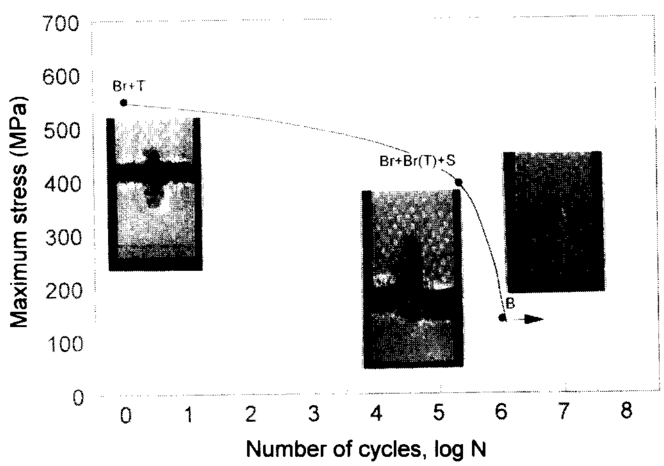

Figure 12 *S–N* curves for autoclave cured Brochier laminates

nates. Limited data indicated that the optimum strength for the oven cured laminates was achieved at $w/d > 7$.

Fatigue bearing behaviour

The fatigue *S–N* curves for various laminates are presented in *Figures 10–13*. Some of the curves include only a few data points. However, it is clear that a fatigue endurance limit (to enable a fatigue life $N \geq 10^6$ cycles) may only be achieved at stress levels as low as 25% of the static failure stress (bearing strength).

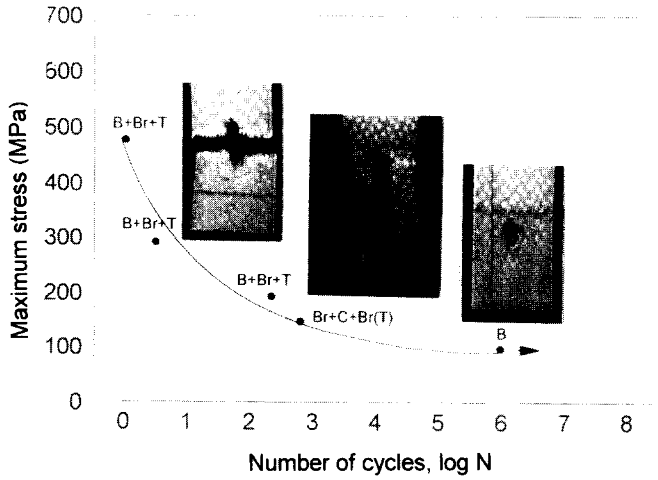

Figure 13 *S–N* curves for oven cured Brochier laminates

The specimens which did not fracture up to $N = 10^6$ suffered limited pin displacement by bearing, as can be seen in the relevant photographs in *Figures 10–13*. At higher stress levels, the fatigue failure was accompanied by initial pronounced remote bearing (Br) at the washer edge and final failure by net tension, particularly at (fatigue stress amplitude)/(static strength) ratios >50%, and by a cleavage–tension combination at (stress amplitude)/(static strength) ratios in the range 25–50%.

CONCLUSIONS

The resistance of woven Kevlar fibre/epoxy resin laminates to pin bearing is highly sensitive to the lateral constraint imposed on the pin. An ~100% increase in bearing strength is indicated using merely finger-tightened bolts. The enhancement effect due to the constraint is associated with a change in the ultimate failure mode from bearing to net tension.

Hygrothermally conditioned specimens, resulting in 2% moisture absorption, suffer only a relatively small reduction (~10%) in bearing strength under bolted conditions. Greater variations in performance are shown depending on the extent of laminate consolidation (i.e. autoclave *versus* oven cured laminates) and the type of resin used. The extent of laminate consolidation also affects the selection of specimen geometric parameters, such as width/diameter (w/d) ratios, for the achievement of optimum bearing strength (for example, $w/d > 6$ and $w/d > 7$ are required, respectively, for autoclave and oven cured laminates).

A low fatigue endurance limit (identified as the maximum stress at which a fatigue life $N \geq 10^6$ is obtainable) is indicated for the Kevlar fibre/epoxy resin laminate, which coincides with ~25% of the ultimate static failure stress. The fatigue failure mode obviously depends on the stress amplitude. It changes from a mainly tensile to a mainly bearing type of failure as stress amplitude decreases.

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